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METHANE EMISSION FROM DIRECT SEEDED RICE UNDER THE INFLUENCES OF RICE STRAW AND NITRIFICATION INHIBITOR

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ABSTRACT

Incorporation of rice straw into soil is a common practice to improve soil productivity and increase inorganic fertilizer availability. However, this practice could contribute to methane (CH_4) emission; one of the greenhouse gases that causes global warming. Nitrification inhibitors such as neem cake and carbofuran may reduce methane emission following application of rice straw. The study aimed to evaluate the application of rice straw and nitrification inhibitor to methane emission in rainfed lowland rice system. A factorial randomized block design was used with three replications. The first factor was rice straw incorporation (5 t ha^{-1} fresh straw, 5 t ha^{-1} composted straw), and the second factor was nitrification inhibitor application (20 kg ha^{-1} neem cake, 20 kg ha^{-1} carbofuran). The experiment was conducted at rainfed lowland in Pati, Central Java, during 2009/2010 wet season. Ciherang variety was planted as direct seeded rice with spacing of 20 cm x 20 cm in each plot of 4 m x 5 m. The rice straw was treated together with soil tillage, whereas nitrification inhibitor was applied together with urea application. Parameters observed were methane flux, plant height, plant biomass, grain yield, organic C content, and bacterial population in soil. The methane flux and soil organic C were measured at 25, 45, 60, 75, and 95 days after emergence. The results showed that composted rice straw incorporation significantly emitted methane lower (73.2 ± 6.6 kg CH_4 ha^{-1} $season^{-1}$) compared to the fresh rice straw (93.5 ± 4.0 CH_4 ha^{-1} $season^{-1}$). Application of nitrification inhibitors neem cake and carbofuran reduced methane emission as much as 20.7 and 15.4 kg CH_4 ha^{-1} $season^{-1}$, respectively. Under direct seeded rice system, methane flux level correlated with plant biomass as shown by linear regression of $Y = 0.0015 X + 0.0575$ ($R^2 = 0.2305$, n = 27). This means that higher plant biomass produced more methane flux. The study indicates that application of nitrification inhibitors such as neem cake is prospective in decreasing methane emission from direct seeded rice cropping.

[***Keywords***: Methane, direct seeded rice, rice straw, nitrification inhibitors]

INTRODUCTION

Management of rainfed lowland in supporting food safety is facing serious constraints such as low soil fertility, therefore efforts to increase soil fertility through organic matter application is important in maintaining high crop yields. Amendment of organic matters such as rice straw into soil increases soil productivity because it will enhance essential nutrient availability which can improve both soil physical and biological properties. Incorporation of 5 t ha^{-1} rice straw could supply 150 kg N, 20 kg P, 150 kg K, 20 kg S, 20 kg Ca, 5 kg Mg, and 300 kg Si into soil and improve soil structure resulting in higher grain yield (Ponnamperuma 1984).

Rainfed lowland farmers commonly incorporate rice straw into soil in various forms such as fresh, composted and burned straws after harvesting. Despite its nutrient contribution, application of rice straw in rice fields can stimulate the emission of methane (CH_4) (Neue *et al*. 1990). Satpathy *in* Sethunathan *et al*. (2000) reported that methane emitted following amendment of various organic matters under submerged soil condition varied, where green manure > cellulose > rice straw > compost of Anabaena > compost of Azolla > farmyard manure.

The lower inorganic N fertilizer efficiency in rainfed lowland rice soils is influenced by N losses through NH_3 volatilization, nitrification-denitrification, run off, and leaching (De Datta *et al*. 1991). The use of nitrification inhibitor materials in rice cultivation is one option to increase N uptake and N fertilizer efficiency. Application of nitrification inhibitors will affect methane emission, however, the mechanism involved in mitigating methane production and emission is not fully understood. Some nitrification inhibitor materials such as neem cake and carbofuran might reduce the population of methanogens. They also act as oxidants and are able to maintain the redox potential of flooded soil system. Nitrification inhibitor might control methane emission through methane oxidation by influencing methane monoxygenase enzyme (Sahrawat 2004). Neem cake has a well-known antibacterial effect due to tannin or polyphenol contents that inhibit methanogenic activity. Application of carbofuran at 2 and 12 kg active ingredient (a.i.) ha^{-1} reduced methane emission from flooded rice soils (Kumaraswamy *et al. in* Sahrawat 2004).

Methane is one of the main greenhouse gases that contributes directly to global warming by absorbing outgoing tropospheric infrared radiation. The atmospheric methane concentration at present is 1,720 ppbv, more than twice found in the pre-industrial era (1750-1800) of about 700 ppbv. Its concentration increases at the rate of 0.9% $year^{-1}$ and the total annual methane emission is about 500 Tg, exceeding the total sink of 37 Tg $year^{-1}$ (Tg = 10^{12} g or million tonnes) (Khalil and Rasmussen *in* Sethunathan *et al.* 2000).

Rice fields are considered to be an important anthropogenic source for methane. According to Lelieveld *et al. in* Sethunathan *et al.* (2000), global methane emission rate from wetland rice fields is estimated about 60 Tg $year^{-1}$, ranging from 20 to 100 Tg $year^{-1}$. Approximately 80% of total methane emission is derived from biological processes (Kerdchoechuen 2005); more than 20% or ~100 Tg $year^{-1}$ is emitted from rice fields (Prinn 1994).

Methane is the final product of organic matter decomposition under anaerobic condition. Methane generation involves methanogenic bacteria such as *Methanosarcina*, *Methanobacterium*, and *Methanococcus* (Neue and Roger 1994). Most of methanogenic bacteria are neutrophylic with optimum pH in range of 6-8 (Neue 1993). Methane emission from flooded rice soils occurs through plant-mediated rice plant aerenchyma, ebullition, and diffusion (Conrad 1996).

Methane is produced from rice fields based on interaction processes in soil that involve rice plant and microorganisms. Flooding rice fields promotes anaerobic fermentation of carbon sources supplied by the rice plant and other incorporated organic substrates resulting in methane production. The growing rice plant produces root exudates and dead root tissues which are available as substrates for methanogens. The magnitude of methane emission from rice plant is regulated by complex and dynamic interaction of plant, environment, and microorganisms (Das and Baruah 2008). According to Wassmann *et al.* (2000), methane emission is the interactive product of three processes, namely (1) methane production controlled by Eh, pH, mineralizable C, and temperature; (2) methane oxidation controlled by oxygen diffusion through the rice plant; and (3) vertical transfer controlled by water depth and rice plant growth stages.

Mitigation of methane emission from rice field should integrate several cultural practices. Setyanto and Abubakar (2006) reported some cultural practices that could reduce methane emission, i.e. water management, rice cultivar, planting method, and urea tablet application. Intermittent or pulse irrigation could suppress methane emission of about 48.6% and 58.9% compared with continuous flooding (Setyanto and Abubakar 2005). The early-maturing Dodokan rice variety emits methane lower than the late-maturing Cisadane, and the high-yielding varieties IR64 and Memberamo have moderately high emission rates. Deep placement of urea tablet decreases methane emission rates by 39% in wet season as compared with broadcasting of prilled urea (Setyanto *et al.* 2000).

The general cropping pattern at rainfed lowland is direct seeded rice in the wet season followed by transplanting rice in the beginning of dry season and followed by upland food crops. In direct seeded rice system, rice seeds are planted with dibbling in unpuddled field and submerged later. On the other hand in transplanting system, rice seedlings are transplanted in puddle field. The crop establishment will affect the magnitude of methane production and emission.

Information about methane emission from nitrification inhibitor use in Indonesia is relatively rare. This study aimed to investigate the influence of rice straw and nitrification inhibitor on methane emission from direct seeded rainfed lowland rice cropping.

MATERIALS AND METHODS

Experimental Site

A field experiment was carried out in rainfed lowland at Pati, Central Java, during 2009/2010 wet season. Experimental site was in Sidomukti Village of Jakenan Subdistrict (111°10’ E, 6°45’ S, 15 m above sea level, Oldeman climate type of E2–E3). The site was a representative for rainfed lowland in Central Java that covers about 150,000 ha. The soil at the site was Vertic Endoaquepts, with 15% clay and 43% silt at surface layer and 23% clay and 40% silt at subsoil layer. The surface soil (0-20 cm) was moderately acid (pH-H_2O 5.6), low total N content (0.3 mg g^{-1}), low organic C (3.2 mg g^{-1}), low Bray extractable P (5.06 mg kg^{-1} P), low CEC (6.96 cmol(+) kg^{-1}), and low exchangeable cations of K, Na, Ca, and Mg namely 0.12, 0.24, 3.05, and 0.61 cmol(+) kg^{-1}, respectively.

Experimental Design

The experiment was arranged in a factorial randomized block design with three replications. The first factor was rice straw application that consisted of three treatments, namely without rice straw, incorporation of 5 t ha^{-1} fresh rice straw, and incorporation of 5 t ha^{-1} composted rice straw. The fresh rice straw used was originated from previous cropping season under minimum tillage transplanted rice, whereas the composted rice straw was from the last two-season direct seeded rice straw which was heaped in the field during the last season. The second factor was application of nitrification inhibitor consisted of three treatments, namely without nitrification inhibitor, application of 20 kg ha^{-1} neem cake, and incorporation of 20 kg ha^{-1} nematicide containing carbofuran active ingredient. According to Sahrawat (2004), neem grains and carbofuran are two materials categorized as nitrification inhibitor.

Experimental Procedure

The unflooded soil was plowed and harrowed for land preparation. Plot size was 4 m x 5 m. The composite soil sample was taken from 0-20 cm depth before planting rice to analyze initial soil properties. Rice seeds of Ciherang variety were planted using dibble with 3-5 seeds per hill and plant spacing of 20 cm x 20 cm on 19 November 2009. The seeds germinated on 2 December 2009. The rice straw was incorporated during soil tillage and the land was ready planted after two weeks of rice straw incorporation.

Nitrification inhibitor materials were applied together with basal inorganic fertilizers. The rates of inorganic fertilizers were based on the site recommendation, namely 120 kg N, 10 kg P, and 25 kg K ha^{-1}. N fertilizer (urea) was applied in splits, namely 1/3 before planting, 1/3 at active tillering stage, and 1/3 at panicle initiation stage. P fertilizer was applied before planting, while K fertilizer was applied 1/2 dose before planting and 1/2 dose at panicle initiation stage. Plant maintenance was done intensively according to site recommendation. Pest and disease control was conducted depending on the infestation. The direct seeded rice was harvested on 10 March 2010.

Data Collection

Variables observed were methane flux, plant height, plant biomass, grain yield, soil organic C content, and bacterial population in soil. Plant height was measured at maturity stage randomly from 12-hill samples per plot. Methane flux was measured using closed chamber method at several plant growth stages, namely early growth (25 days after germination = DAG), active tillering (45 DAG), maximum tillering (60 DAG), heading (75 DAG), and maturity (95 DAG). During gas sampling, soil sample was taken from the surrounding rice roots using a soil auger for determining organic C content with Walkley & Black method. Soil bacterial population was determined using the Most Probable Number (MPN) method at maximum tillering stage by taking composite soil sample surrounding the rice roots.

Gas samples were collected from closed plexiglas chambers. The size of the chambers was 40 cm x 40 cm base x 60 or 120 cm height depending on plant height at sampling time. Each chamber was installed with a septum, a fan, and a thermometer on the cover. The chamber was laid randomly in each plot and the following sampling used the same position as the first one.

Gas samples were drawn at 5, 10, 15, and 20-minute intervals after closing the chamber using 10 ml syringes. The fan was used to mix the gas inside the chamber. Drawing air out of the chamber head space into a syringe and releasing it back into the chamber (8-10 times) before the final sample withdrawal was an attempt to flush the syringe. Methane concentration in the gas samples was determined with a gas chromatography equipped with a flame ionization detector (FID) and a porapak N stainless steel column (80/100 mesh, 0.3 cm x 2.0 m) at 40°C. Nitrogen was used as the carrier gas at a flow rate of 30 ml minute^{-1} and a methane standard of 10.1 ml l^{-1} was employed. Methane flux was calculated using equation as follows (Lantin *et al*. 1995):

$$E = \frac{dc}{dt} \cdot \frac{Vch}{Ach} \cdot \frac{Wm}{Vm} \cdot \frac{273.2}{273.2 + T}$$

E = CH_4 flux (mg m^{-2} minute^{-1})
dc/dt = CH_4 rate per time (µl l^{-1} minute^{-1})
Vch = chamber volume (m^3)
Ach = chamber area (m^2)
Wm = molecular weight of CH_4 (16 x 10^3 mg)
m = volume of 1 mole of gas at standard temperature and air pressure (22.41 x 10^{-3} m^3)
T = average temperature inside the chamber during gas sampling (°C)

Data Analysis

The collected data was analyzed with SAS for Window Release 9 using the analysis of variance to determine treatment significance. The analysis was continued with least significant difference test to determine comparison between treatment means.

RESULTS AND DISCUSSION

Methane Flux Pattern

Figure 1 shows methane flux pattern from direct seeded rice cropping. The low methane flux occurred at 25 DAG because soil during the early growth stage of direct seeded rice was dry or aerobic. Methane flux increased gradually at active tillering stage (45 DAG) and reached a peak at maximum tillering to heading stages (60-75 DAG), then decreased gradually at maturity stage, except in treatments of without nitrification inhibitor and with neem cake. In treatments of without rice straw and with fresh rice straw, methane flux pattern at maturity stage tended to increase if no nitrification inhibitor or with neem cake was added. The peaks of methane flux occurred at heading stage, except in treatment of carbofuran application combined with fresh rice straw incorporation.

The cumulative methane fluxes of rice straw treatments were in the order of without rice straw < composted rice straw < fresh rice straw. The order of cumulative methane fluxes from nitrification inhibitor treatments was neem cake < carbofuran < without nitrification inhibitor. Nitrification inhibitor application seems to suppress methane flux more effectively than without nitrification inhibitor. The high cumulative methane fluxes occurred in control treatment (without rice straw and without nitrification inhibitor), combination of fresh rice straw incorporation + carbofuran application, and combination of composted rice straw incorporation + without nitrification inhibitor (Fig. 2). Application of nitrification inhibitor suppressed methane flux more effectively both in plots incorporated with composted rice straw and in plots without rice straw, whereas application of nitrification inhibitor in plots incorporated with fresh rice straw increased methane flux.

Methane flux from early growth stage to active tillering stage occurred through ebullition process, whereas methane flux at maximum tillering or panicle initiation and heading stages was through rice plant-mediated aerenchyma tissue. Aerenchyma tissue is the intercellular space in rice plant cortex of stem and root where gas exchange occurs between the atmosphere and soil environment (Kludze *et al*. 1993). That tissue acts as chimney for releasing methane to the atmosphere. According to Holzapfel-Pschorn *et al*. (1986), up to 90% of methane produced to atmosphere occurred through rice plant aerenchyma tissue.

The high methane flux at vegetative growth stage in flooded rice soils occurred due to the high avail-

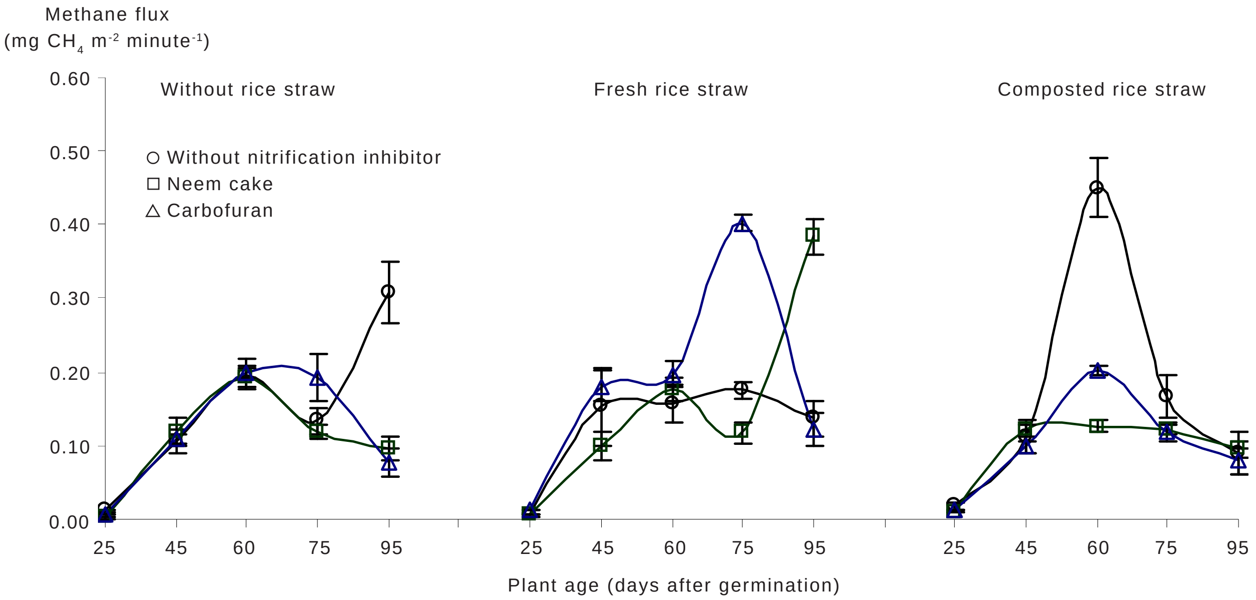

Fig. 1. Methane flux patterns from direct seeded rice cropping treated with combination of rice straw incorporation and nitrification inhibitor application, Jakenan, Pati, Central Java, 2009/2010 wet season.

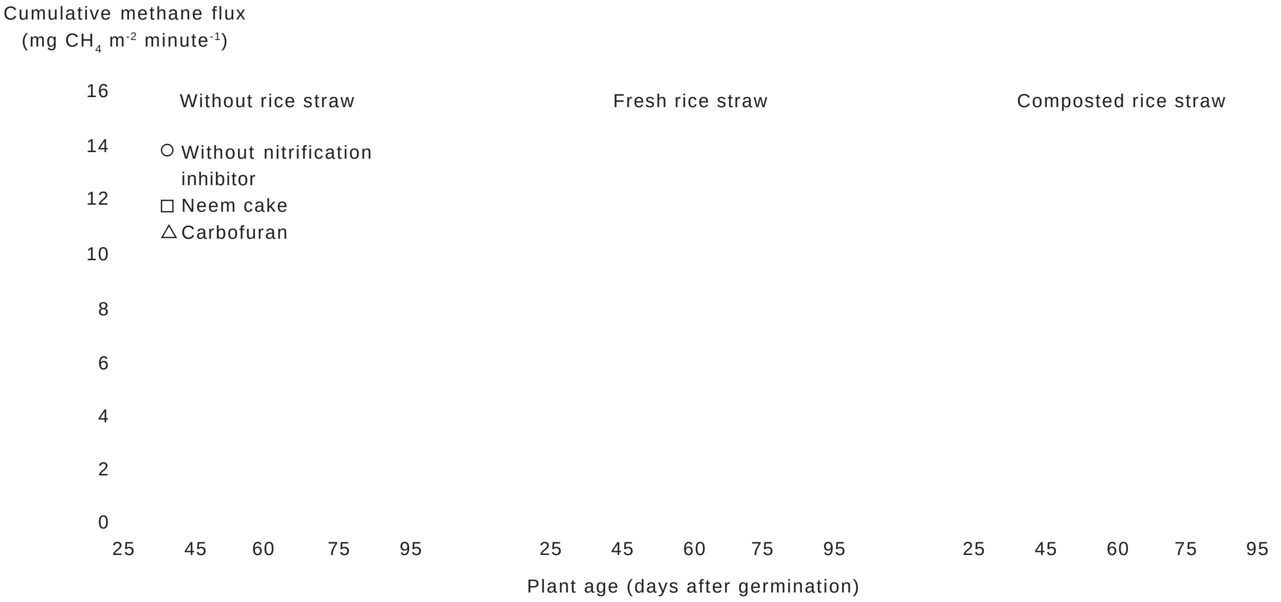

Fig. 2. Cumulative methane flux patterns from direct seeded rice cropping treated with combination of rice straw and nitrification inhibitor, Jakenan, Pati, Central Java, 2009/2010 wet season.

ability of organic substrates from root exudates (Neue and Sass 1994). Root exudates contain acetic acid higher at vegetative growth stage than at grain filling stage (Kerdchoechuen 2005). Acetic acid and H_2 in flooded rice soils are substrates or precursor of methane formation (Dubey 2005). Root exudation at vegetative growth stage is affected by the rapid carbon translocation in rhizosphere due to increasing photosynthetic rate (Iqbal *et al*. 2009).

Incorporation of fresh rice straw resulted in a higher methane flux than that of composted rice straw. Application of rice straw as organic amendment could enhance available organic C content in soil (Iqbal *et al*. 2009). When the soil is submerged, as temperature increases, rice straw decomposes rapidly to produce methane under anaerobic condition (Ko and Kang 2000), and application of rice straw compost significantly reduces methane emission as opposed to fresh rice straw (Wassmann *et al*. 2000). The fresh rice straw contains total organic C higher than the composted rice straw (Fig. 3), namely 41.98% in fresh rice straw and 19.89% in composted rice straw. The organic C content in both rice straw influences the final products of anaerobic decomposition, such as methane production in rice soil applied with fresh rice straw was higher than that of composted rice straw. Minami (1995) reported that methane production from applying fresh straw was higher than that of composted rice straw attributed to the high decomposition rate and a high degradable organic matter content.

Effect of Soil Organic C Content in Rice Rhizosphere

The increase in methane flux at certain growth stages relates with organic substrate availability in rice rhizosphere, especially at vegetative growth stage. Figure 3 shows fluctuation of soil organic C content at growth stages of Ciherang rice variety planted with direct seeded system. Soil organic C content in rhizosphere increased at active tillering stage (45 DAG). Soil organic C content at active tillering and maximum tillering stages ranged between 8.4-13.0 mg g^{-1} and 4.5-7.2 mg g^{-1}, respectively.

The high organic C content in rice rhizosphere occurred at maximum tillering stage. Availability of organic C in such growth stage stimulates methanogenic bacteria to actively produce methane gas because of organic substrate availability from rice root exudation (Das and Baruah 2008). The methane flux at reproductive growth stages will be high if organic C supply is available from root exudates and the toxic substance does not inhibit methanogen activity (Kerdchoechuen 2005). Neither root exudates nor root autolysis products contain sugar, amino acids, and organic acids which are readily available substrates for methanogenic bacteria activity (Holzapfel-Pschron *et al*. 1986; Kludze *et al*. 1993). Up to 50% of total methane emission from rice soils is affected by root exudation (Dubey 2005).

The methane release at certain growth stages is affected by population and activity of microorganisms based on organic substrate availability and soil water content. Total bacterial population at maximum tillering stage played an important role in affecting methane production under direct seeded rice cropping. Total bacterial population in treatment of fresh rice straw incorporation was lower than that of composted rice straw incorporation, however, the higher methane flux occurred in treatment of fresh rice straw (Fig. 4). This may be due to a higher methanogenic bacterial population than methanotropic bacterial population at maximum tillering stage. According to Wang and Adachi (2000), rhizospheric bacteria consisted of methanogenic and methanotropic bacteria. The population of methanogenic bacteria that depend on the availability of C sources was significantly different at tillering, booting, and ripening stages among rice cultivars. Conversely, the population level of methanotropic bacteria among rice cultivars differed only in roots at ripening stages.

The decrease in methane flux is affected by the existence of methanotropic bacteria in rice rhizosphere which could partly transform CH_4 to CO_2.

Fig. 3. Soil organic carbon in rhizosphere of direct seeded rice cropping treated with rice straw and nitrification inhibitors, Jakenan, Pati, Central Java, 2009/2010 wet season.

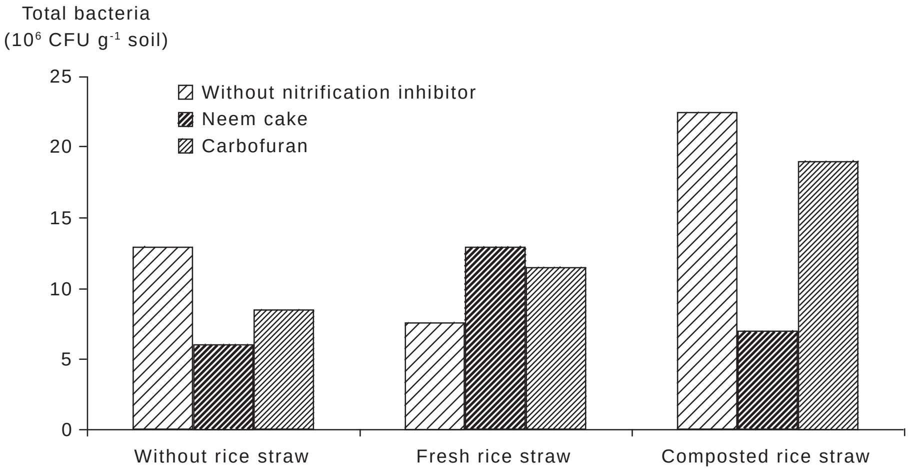

Fig. 4. Total bacterial population in rhizosphere of direct seeded rice cropping at maximum tillering stage trated with rice straw and nitrification inhibitor, Jakenan, Pati, Central Java, 2009/2010 wet season. CFU = colony forming unit.

Methane flux could increase at certain concentration of organic C in soil, however, other microorganisms such as methanotropic bacteria also need organic C to oxidize CH_4 to CO_2 (Ko and Kang 2000). Organic C availability in rice rhizosphere derives from root exudates and root decay which could be used by methanogenic bacteria as energy sources to methane formation (Kerdchoechuen 2005). According to Wassmann *et al*. (2000), carbon compound exudation in reductive soil condition could be used by methanogenic bacteria directly and indirectly. The decrease in root exudates reduces methane production and emission, so that photosynthate like sugar and carbon dioxide could be uptaken by plant for increasing its production (Wassmann *et al*. 1993).

Methane Emission from Direct Seeded Rice Cropping

Methane emission from diect seeded rice cropping was 58-112 kg CH_4 ha^{-1} $season^{-1}$. Under direct seeded system, rice seeds are planted in dry condition and rice field starts flooded condition at active tillering stage (30 DAG) that affected methane production. Incorporation of rice straw in direct seeded rice cropping increased significantly methane emission about 12.4 kg CH_4 ha^{-1} $season^{-1}$ ($p < 0.0001$) (Table 1). The average methane emissions in plots treated with fresh rice straw and composted rice straw were 93.5 ± 40 kg and 73.2 ± 6.6 kg CH_4 ha^{-1} $season^{-1}$, respectively.

Application of nitrification inhibitor materials ($p < 0.01$) and its interaction with rice straw incorporation ($p < 0.0001$) affected significantly methane emission (Table 1). Application of nitrification inhibitor significantly reduced average methane emissions from direct seeded rice cropping, namely 20.7 kg CH_4 ha^{-1} $season^{-1}$ with applying neem cake and 15.4 kg CH_4 ha^{-1} $season^{-1}$ with applying carbofuran. Effect of neem cake seems more effectively to reduce methane as compared with carbofuran. Inhibition of methane emission using neem cake might be related to lower population of methanogenic bacteria. According to Sahrawat (2004), neem cake as nitrification inhibitor might reduce the population of methanogenic bacteria, so that the bacterial metabolism generates low methane.

Methane emission from incorporating composted rice straw was not significantly different from that of without rice straw. This is because organic matter amendments with lower C/N ratio would give the lower methane emission. The fresh rice straw incorporation increases methane production and emission by enhancing soil reduction and providing additional carbon sources (Neue and Sass 1994). Application of composted rice straw significantly reduced methane emission as opposed to fresh rice straw. Composted rice straw incorporation may offer a number of benefits for soil fertility and tillage as opposed to fresh rice straw (Wassmann *et al*. 2000). Yagi and Minami (1990) also reported that addition of 6 t ha^{-1} rice straw into soil increased methane emission of 1.8-3.3 times, and incorporation of 9 t ha^{-1} rice straw released methane to atmosphere of more than 3.5 times compared to inorganic fertilizer application alone.

The highest methane emission was obtained in plots applied with combination of fresh rice straw and carbofuran with flux of 112 ± 4 kg CH_4 ha^{-1} $season^{-1}$ (Table 1). Methane emission from plot treated with composted rice straw alone was not significantly

Table 1. Effect of rice straw incorporation and nitrification inhibitor application on methane emission and grain yield of direct seeded rice, Jakenan, Pati, Central Java, 2009/2010 wet season.

Rice straw incorporation	Nitrification inhibitor application	Methane emission (kg CH_4 ha^{-1} $season^{-1}$)	Grain yield (t ha^{-1})
Without rice straw	Without nitrification inhibitor	86.7 ± 11.0bc	6.86 ± 0.58bc
	Neem cake	64.9 ± 4.0de	6.78 ± 0.57c
	Carbofuran	71.8 ± 5.0de	7.18 ± 0.68abc
Fresh rice straw	Without nitrification inhibitor	99.1 ± 1.9ab	7.51 ± 0.63ab
	Neem cake	90.4 ± 17.7bc	6.99 ± 0.59bc
	Carbofuran	112.2 ± 4.1a	7.13 ± 0.39bc
Composted rice straw	Without nitrification inhibitor	77.9 ± 9.8cd	7.80 ± 0.29a
	Neem cake	58.3 ± 1.9e	7.40 ± 0.53abc
	Carbofuran	62.1 ± 3.6e	7.73 ± 0.43a
CV (%)		10.17	5.35

Total methane emission per cropping season was computed for one growth period, which was 100 days.
Means in same column followed by the same letter are not significantly different according to LSD test at 5% level.

different from plots without rice straw. The lowest methane emission was obtained in plots treated with composted rice straw + neem cake followed by treatment of composted rice straw + carbofuran with flux of 58 ± 2 kg and 62 ± 4 kg CH_4 ha^{-1} $season^{-1}$, respectively. Application of fresh rice straw + nitrification inhibitor increased methane emission, whereas nitrification inhibitor application in plot combined with composted rice straw reduced methane emission. The high methane production occurred if rice soils are applied with organic amendments containing high C/N ratio including fresh rice straw, under which condition so that application of nitrification inhibitor seems ineffective to reduce methane emission. On the other hand, nitrification inhibitor is more effective to reduce methane emission from rice soils incorporated with composted rice straw.

Rice straw incorporation into soil significantly increased the grain yield of direct seeded rice ($p < 0.01$), however, its interaction with nitrification inhibitor application was not significantly different. The fresh and composted rice straw application increased grain yield as high as 4% and 10%, respectively (Table 1). Rice straw with appropriate management could reduce greenhouse gas emission, improve soil fertility, and increase rice grain yield. However, farmers in rainfed lowland usually remove rice straw after harvesting for feeding their cattle.

Ratio between methane emission and grain yield could be used as an index of methane production from rice fields. The highest ratio of 0.016 was found in treatment of fresh rice straw + carbofuran. Treatment of composted rice straw application combined with nitrification inhibitors gave the lowest index, namely 0.008 (Fig. 5). Such value indicates that nitrification inhibitors reduce methane emission per unit weight of grain yield.

The neem seeds are abundant in some regions of Java, especially in surrounding the rainfed lowland rice areas. Farmers have been using it as an organic pesticide. In the future, neem seed management gives a better prospect as nitrification inhibitor for coating N fertilizer to increase N fertilizer efficiency and decrease greenhouse gases emission from agricultural lands. However, this implies a higher demand for neem cake that is also currently used for other purposes, such that neem tree planting should also be promoted.

Relationship between Methane Flux and Rice Growth

Plant height could be used as one of plant growth indicators. Plant height of rainfed lowland rice correlated positively with the magnitude of methane released to the atmosphere as shown by a linear regression of $Y = 0.0051 X – 0.1766$ ($R^2 = 0.3027$, n = 27, p = 0.018) where Y is methane flux and X is rice plant height (Fig. 6). It is predicted that the better plant growth affects the development of aerenchyma tissue in plant sheath leaf, stem, and roots so that root exudates produce more organic substrates (Schutz *et al. in* Kerdchoechuen 2005). Aerenchyma tissue is a chimney for releasing methane from flooded rice soils to the atmosphere. According to Wang *et al.* (1992), up to 95% methane produced from rice soils is translocated through aerenchyma system and its rate is based on plant growth stages, diurnal fluctuation of photosynthesis, and respiration rate.

Under direct seeded rice system, methane flux correlated with plant biomass as shown by linear regression of $Y = 0.0015 X + 0.0575$ ($R^2 = 0.2305$, n = 54, p = 0.001), where Y is methane flux and X is plant biomass weight per hill (Fig. 7). This means that

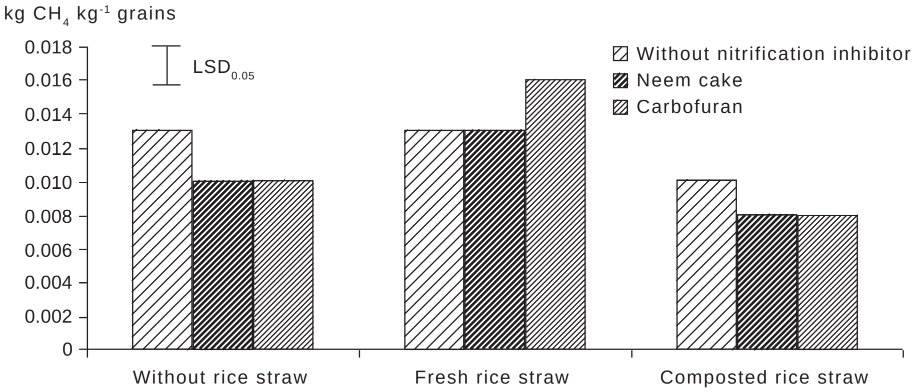

Fig. 5. Ratio between methane emission and grain yield of direct seeded rice of Ciherang variety treated with rice straw and nitrification inhibitor, Jakenan, Pati, Central Java, 2009/2010 wet season.

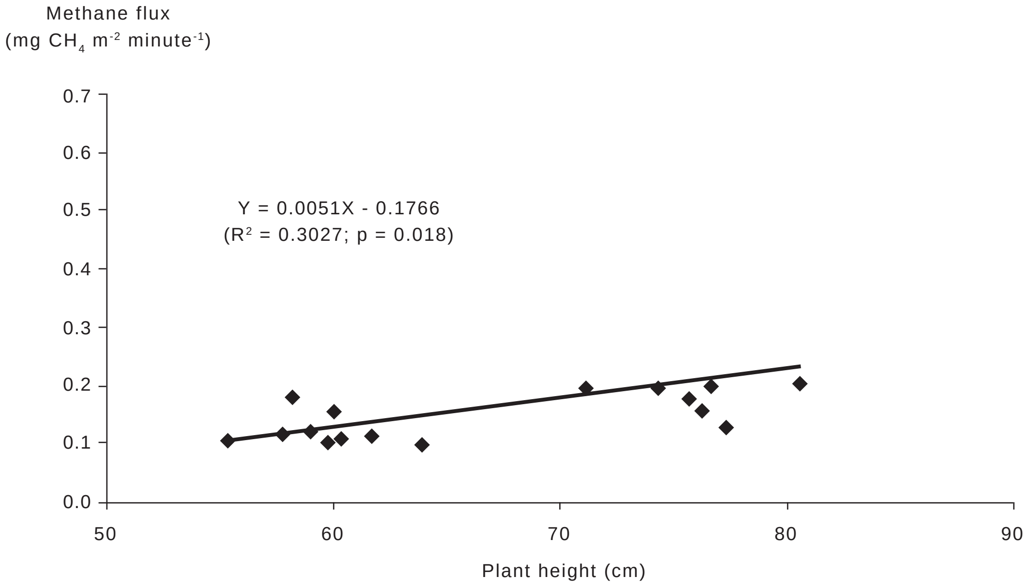

Fig. 6. Relationship between methane flux and plant height of direct seeded rice at 95 days after germination, Jakenan, Pati, Central Java, 2009/2010 wet season.

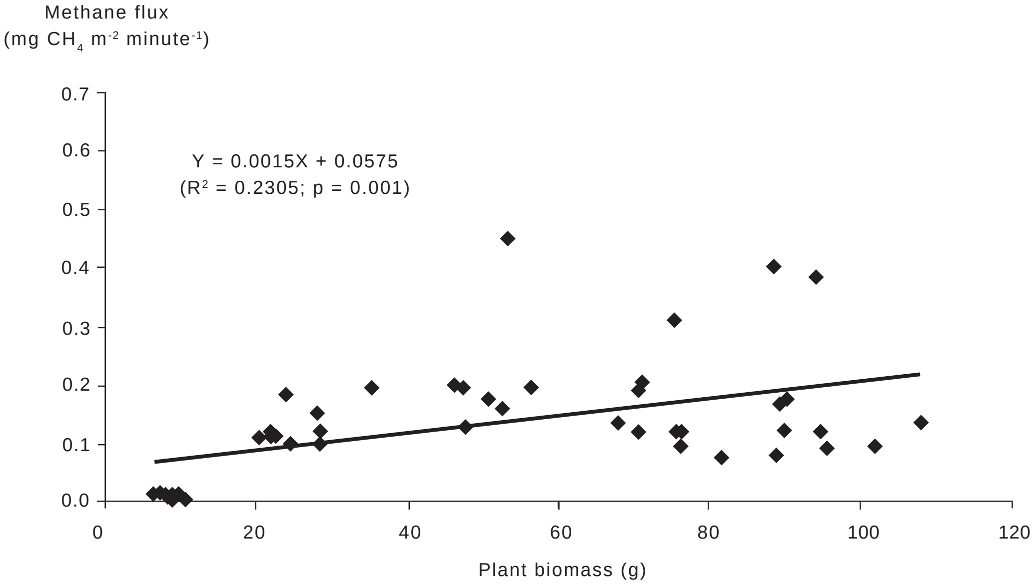

Fig. 7. Relationship between methane flux and rice plant biomass per hill of direct seeded rice at 95 days after germination, Jakenan, Pati, Central Java, 2009/2010 wet season.

higher plant biomass production increases more methane flux.

This study indicates that mitigation of methane emission in rainfed rice system needs an integrated soil and plant management such as adoption of intermittent irrigation or alternative drainage on flooded rice soils during vegetative growth stage, using rice cultivars with the high methane-oxidizing power and relatively low root exudates. According to Setyanto and Abubakar (2006), O_2 diffusion from rice roots and abundant methane-oxidizing bacteria present in the rhizosphere, provide a high potential for methane oxidation. The lower rhizospheric methane oxidation rates at late tillering stage resulted in higher methane flux in rice soils. Methanogenic bacteria use root exudates as substrates to produce methane gas in flooded rice soils (Wang *et al*. 1992; Das and Baruah 2008). Root exudates and decaying roots are carbon sources for methane production. Neue and Sass (1994) found significant positive correlations between root biomass and methane production, and between above ground biomass and methane emission. Das and Baruah (2008) also reported that the number of plant tillers is positively correlated with methane emission rate.

CONCLUSION

Carbon and nitrogen contents in organic soil amendments determine the magnitude of methane fluxes. Application of composted rice straw with low C/N ratio resulted in lower methane emission than high C/N ratio fresh rice straw incorporation.

Application of nitrification inhibitor material neem cake in direct seeded rice decreased significantly methane emission, especially when applied together with composted rice straw into rice soils. Application of neem cake decreased significantly average methane emission relative to that of carbofuran application.

Methane flux from rice soils is correlated significantly with rice plant height and biomass. Application of composted rice straw and nitrification inhibitor effectively reduced methane emission without reducing rice yield.

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